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## **Partitioned off-fault deformation in the 2016 Norcia earthquake captured by differential terrestrial laser scanning**

**L. N. J. Wedmore<sup>1\*</sup>, L. C. Gregory<sup>1</sup>, K. J. W. McCaffrey<sup>2</sup>, H. Goodall<sup>1</sup> and R. J. Walters<sup>3</sup>**

<sup>1</sup>Institute of Geophysics and Tectonics, School of Earth and Environment, University of Leeds, Leeds, UK.

<sup>2</sup>Department of Earth Sciences, Durham University, Durham, UK.

<sup>3</sup>COMET, Department of Earth Sciences, Durham University, Durham, UK

Corresponding author: Luke Wedmore ([luke.wedmore@bristol.ac.uk](mailto:luke.wedmore@bristol.ac.uk))

\*Now at Department of Earth Sciences, University of Bristol, UK.

### **Key Points:**

- The first known example of an earthquake rupture imaged with pre- and post-earthquake terrestrial laser scanning
- We differenced the laser scans using an iterative closest point algorithm refined for accurately resolving cm-scale offsets
- We find that off-fault deformation is strongly partitioned between the horizontal and vertical components of displacement

## **Abstract**

Field measurements of co-seismic fault slip often differ from surface slip models derived from satellite geodesy. Quantifying these differences is challenging as many geodetic techniques inadequately image near-fault deformation. We use an iterative closest point (ICP) algorithm to difference pre- and post-earthquake terrestrial laser scanning (TLS) point clouds to reveal cm-scale patterns of surface deformation caused by shallow fault slip in the 2016  $M_w$  6.6 Norcia (central Italy) earthquake. TLS offsets are constant along the fault and match average field measurements. 84% of vertical displacement occurs on a discrete fault zone, with 16% of deformation distributed across a narrow zone  $<4$  m wide. In contrast, horizontal deformation is distributed over an 8 m wide zone with c. 50% of extension accommodated as off-fault deformation (OFD). The cm-scale observation of deformation shows that horizontal and vertical co-seismic OFD is partitioned – in this case, OFD is dominated by horizontal deformation.

## **Plain Language Summary**

During an earthquake, slip on a fault plane creates discrete offsets at depth and at the surface. The pattern and size of offsets at the surface can help to understand what happened in the earthquake, and also leaves a record of each event in the landscape. This record is used to infer past earthquake activity and forecast the potential likelihood of future earthquakes. We captured a pre-earthquake image of a fault which caused the 2016 magnitude 6.6 Norcia earthquake in central Italy. By re-imaging the same fault after the earthquake, we measured the pattern of ground movement during the event to mm precision to understand in unprecedented detail how much earthquake slip occurs on the fault itself. This uniquely precise map of surface deformation has never been captured before using a terrestrial laser scanner. We find that the vertical motion

of the fault is mainly focused on the fault itself. In contrast, the horizontal motion is distributed over an 8m wide zone, with approximately 50% of the movement occurring away from the fault – known as off-fault deformation. Our results have implications for how evidence of past earthquakes preserved in the landscape are interpreted for forecasting future seismic hazard.

## 1 Introduction

Most evidence for pre-instrumental earthquakes comes from palaeoseismic trenches and geomorphic observations of fault offsets collected in the few meters surrounding a fault zone. Observations of earthquakes from satellite geodesy have shown that slip in the shallow subsurface often differs considerably from the magnitude and pattern of slip on the deeper portions of the fault (the shallow slip deficit; Fialko *et al.*, 2005). Whether this discrepancy is due to shallow fault zone mechanics is unclear due to limitations of satellite geodetic techniques for resolving surface fault breaks (e.g. Wright *et al.*, 2003). Regardless, there is a fundamental lack of observations of the 3D displacement field of shallow fault zone slip, aside from field-based measurements of fault rupture that are generally only able to record offset across discrete surface ruptures (see Rockwell and Klinger, 2013, and Brooks *et al.*, 2017 for exceptions). Consequently, it is unclear how offsets recorded in palaeoseismic trenches relate to slip in the deeper portions of a fault zone, and the energy and moment release of the seismic events that the palaeo-offsets represent is therefore uncertain. We examine the shallow fault zone behavior during the  $M_w$  6.6 2016 Norcia earthquake in central Italy, which we imaged by differencing pre- and post-seismic terrestrial laser scanning datasets.

High-resolution optical imagery and airborne lidar can capture near-fault earthquake surface deformation that is invisible to other geodetic techniques. For example, whilst Interferometric

Synthetic Aperture Radar (InSAR) has revolutionized how we are able to constrain earthquake slip, the loss of coherence along surface ruptures means that it is not always possible to accurately model both surface and sub-surface displacement. Using Iterative Closest Point (ICP) algorithms to difference pre- and post-earthquake airborne lidar data can reveal near fault deformation (e.g. Nissen et al., 2014). However, this technique requires window sizes that exceed c. 20 by 20 m in order to reduce the errors (Nissen et al., 2012) – larger than the scale at which palaeoseismic and surface slip observations are often made. Similarly, cross-correlation methods on high-resolution optical imagery can operate on sub-meter scale pixels (e.g. Barnhart et al., 2015; Vallage et al., 2015) but can suffer from biases and artifacts introduced by using smoothed surfaces or gridded DEM's during processing (Ayoub et al., 2009), and the technique can only resolve slip in earthquakes with large, meter-scale displacements. Differenced Terrestrial Laser Scanning (TLS) datasets can help bridge this gap by imaging fault displacement in exceptionally high resolution ( $>100$  points/m<sup>2</sup>), allowing better insight into the faulting process (e.g. Wilkinson et al., 2010). To date, pre-and post-seismic TLS datasets of an earthquake surface rupture have not been available for comparison.

We present TLS observations of near-field fault slip from a section of fault that ruptured in the 2016 central Italy earthquake sequence. The sequence featured three  $M > 6$  earthquakes over a period of 3 months that combined to rupture the Mt Vettore – Mt Bove fault system (Figure 1; Walters et al., 2018). On 29<sup>th</sup> October 2016, we collected TLS data on a section of the Mt Bove fault that ruptured in the  $M_w$  6.1 Visso earthquakes on 26<sup>th</sup> October 2016. Whilst initially collected as a post-earthquake dataset, these data became a pre-earthquake dataset for the  $M_w$  6.6 Norcia earthquake that ruptured the same fault segment on 30<sup>th</sup> October, 12 hours after our first data collection. We returned to the site and collected a post-earthquake dataset on 5<sup>th</sup> November

(Figure 1). We difference these pre- and post-earthquake TLS data to document surface deformation caused by shallow fault slip in the Norcia earthquake and map spatial changes in surface deformation to within 0.5 m of the discrete surface rupture. We compare both vertical and horizontal deformation at a range of scales from field measurements collected on the surface rupture to ICP displacements at distances of <1 m, 4 m, and 8 m from the fault. This enables us to identify differences between discrete deformation associated with the surface rupture and off-fault distributed deformation at a range of distances from the fault. We find significant off-fault deformation (OFD) occurs in <8 m wide zones surrounding the fault, and we show that the OFD is strongly partitioned into its horizontal and vertical components.

## 2 Methods

### 2.1 Field data collection

Terrestrial Laser Scanning is a ground based active remote sensing method that is able to collect large volumes of 3D point cloud data ( $10^2$ - $10^4$  points/m<sup>2</sup>; Table 1 and Figure S2). We used a RIEGL VZ-1000 terrestrial laser scanner to collect both pre- and post-earthquake TLS data surrounding a section of the Mt Bove fault during the 2016 central Italy earthquake sequence (Figures 1 & 2). The pre-earthquake scan was globally referenced using 3 registration targets in the footwall of the fault that were surveyed using a differential GNSS system. For the post-earthquake scan, two different scan position datasets were internally tied together using the same pre-earthquake registration target positions. Initial point-cloud processing was carried out using RiSCAN Pro (v 2.4). Due to deformation and tilting of the footwall during the earthquakes, the post-earthquake point cloud was precisely referenced to a portion of the footwall close to the fault by using a point-to-point iterative closest point algorithm (ICP) within Cloud Compare (see

supplementary materials). We manually removed return ambiguities caused by distant topography and applied a spatial filter to remove points closer than 5 cm to each other in CloudCompare; no other filtering of the raw point clouds was applied.

## 2.2 Point cloud differencing

To difference the pre- and post-earthquake point clouds, we used a windowed point-to-plane ICP algorithm within MATLAB that iteratively calculates the rigid body transformation that minimizes the sum of the squared differences between windows of the pre-event point cloud, which are fixed, and windows of the post-earthquake point cloud (Chen and Medioni, 1992; Bouaziz et al., 2013; Nissen et al., 2017). The resulting transformation matrix contains 3 components of displacements ( $t_x$ ,  $t_y$ ,  $t_z$ ) as well as rotations about the x, y and z axes. Whilst this method has been previously used on airborne lidar (e.g. Nissen et al., 2012; 2014; 2017), we carried out synthetic tests on the pre-earthquake point-cloud to determine the ability of the ICP method to resolve displacements using TLS data, and to refine the workflow (see supplementary material). These tests show that the ICP method can accurately resolve vertical displacements on the order of centimeters close to the fault (Figures S3-14). However, close to the surface rupture, the ICP algorithm is unable to precisely fit a rigid body transformation using just the 3 components of translation and consequently introduces rotations to minimize the RMS error (Figure S10). The effect and extent of these rotations can be reduced by applying a sliding window approach, removing solutions that do not converge, and applying a spatial median filter with a 1 m search radius to the ICP transformation results that has the effect of removing significant outliers (Figure S15 and S18). To difference the pre- and post-earthquake TLS data using an ICP algorithm, we subdivide the point-clouds into local windows of 1 m x 1 m, with an additional buffer zone to account for the horizontal displacement during the earthquake. We used

a buffer zone of 0.4 m as this was greater than the largest offset measured without being overly computationally expensive and it did not curtail the histograms of horizontal displacement (Figure 2c). We applied a sliding window of 0.2 m that leads to an 80% overlap between adjacent cells. The spatial median filter was then applied before we resolved the horizontal displacement vectors  $t_x$  and  $t_y$  in the direction perpendicular to the mean strike of the fault. We compare the ICP derived displacements with field measurements collected using conventional field-based methods in the aftermath of the earthquake by the openEMERGE team (Villani et al., 2018).

### 3 Results

The hangingwall of the fault was downthrown by 7-10 cm in the earthquake as shown by the vertical ICP displacements which sharply delineate the discrete surface rupture, even in regions with dense tree cover (Figure 2b). In contrast, the horizontal fault perpendicular displacements show a diffuse transition between the hangingwall and the footwall (Figure 2c). To analyse the difference between the distribution of horizontal and vertical surface displacement (i.e. discrete rupture versus diffuse deformation) we calculate the difference between the ICP displacement in the footwall and hangingwall measured at 0.5-1 m half width distance from the fault, which represents the closest distance from the fault that our ICP method can resolve (see Figure S18), and compare this to the field measurements of surface offset measured on the fault. We also calculate the ICP displacements further away from the fault to estimate the percentage of deformation that is distributed away from the discrete surface rupture.

The vertical ICP displacement calculated by differencing the hangingwall and footwall points within 0.5-1 m of the fault is consistently 5-10 cm along strike (Figure 3a), whereas the field



measurements of rupture throw vary significantly along strike between 0-30 cm (Figure 2a and 3a). When averaged along the 150 m long section in Figure 3, the mean throw (and  $1\sigma$  uncertainty) measured in the field ( $10 \pm 9$  cm) is comparable to the mean vertical displacement between the hangingwall and footwall points measured 5 m from the fault trace ( $7.6 \pm 0.1$  cm – purple line in Figure 3a). Vertical displacement increases from  $6.4 \pm 0.1$  cm close to the fault (0.5 – 1 m) to  $7.6 \pm 0.1$  cm 5 m from the fault but is relatively constant ( $\sim 7.6$  cm) beyond 4 m from the fault (Figure 4a,c). This equates to  $\sim 16\%$  of vertical displacement occurring as off-fault deformation which is restricted to a zone  $< 4$  m wide.

Projecting the horizontal displacements into fault perpendicular motion (compare Figure 2c with Figure S19) reveals a more discrete rupture across the fault than the individual orthogonal horizontal components of the ICP results (Figure S19), although the horizontal data are still noisier than the vertical displacements. The dominant motion is perpendicular to the fault strike (arrows in Figure 2c), consistent with the dip-slip motion expected from a normal fault. The mean horizontal motion of the hangingwall is towards  $244^\circ \pm 35^\circ$  and the mean strike of the fault is  $139^\circ \pm 12^\circ$  (mean and  $1\sigma$ ). The mean fault heave from the field measurements ( $7 \pm 3$  cm) is significantly more than ICP fault perpendicular displacements measured within 1 m from the fault ( $2.8 \pm 0.1$  cm) but comparable to the ICP fault perpendicular displacements measured 5 m away from the fault ( $4.7 \pm 0.1$  cm; Figure 3b). Whilst the ICP displacements do show a discrete surface rupture, the horizontal displacement also increases significantly with distance away from the fault and only becomes constant ( $\sim 5.5$  cm) beyond 8 m from the fault (Figure 4b,d). This equates to  $\sim 50\%$  of the horizontal deformation being accommodated as off-fault deformation in a distributed manner across an 8 m wide zone.

## 4 Discussion and Implications

The high spatial resolution of the dataset that we collected indicates that both vertical and horizontal ICP displacements show evidence of a discrete surface rupture (Figure 2). The ICP derived offsets close to the fault rupture (0.5 – 1 m; our method cannot resolve  $< 0.5$  m – see supplementary material) are generally lower than the field measurements (Figure 3). In contrast, the ICP displacements at greater distances from the fault (4–5 m), are approximately constant along strike and are consistent with the mean of the field measurements within error. A comparison of ICP measurements close to the rupture with those measurements at greater distances indicates that displacement increases in a diffuse manner across a finite zone due to off-fault deformation. This diffuse off-fault deformation is not captured in the field measurements reported by Villani et al. (2018) because the magnitude of the diffuse deformation approaches the resolution of field measurements (although errors are not explicitly stated, they are typically on the order of ~5 cm). In general, traditional field measurements struggle to capture an accurate measure of how *wide* this zone of diffuse deformation is, and thus the amount of off-fault deformation. In contrast, satellite-based geodetic techniques struggle to capture how *narrow* the zone of diffuse deformation is and the nature of the off-fault deformation within the zone. InSAR is limited by pixel size and incoherence across such narrow zones of faulting – Sentinel-1 interferograms across this section of fault are generally incoherent within at least 1 km of the fault (Walters et al, 2018).

Whilst satellite- and field-based methods are sub-optimal for capturing zones of diffuse deformation close to a surface rupture, airborne lidar has proved useful in capturing the 3D near-fault displacement field. The only other example of ICP displacements calculated in a pure normal faulting earthquake known to us was using airborne lidar on the  $M_w$  7.1 Fukushima-

Hamadori earthquake (Nissen et al., 2014). Here they found that the horizontal East-West and North-South ICP displacements were noisy and did not show a discontinuity across the fault rupture, despite a clear vertical signal. We analyse the horizontal displacements in the Norcia earthquake by projecting them into fault perpendicular motion (Figure 2c). Whilst we also find greater noise in the horizontal displacement, we are still able to resolve cm-scale features in the displacement field (Figure 4). We suspect the higher noise may be due to generally smooth horizontal surfaces or the difficulty in horizontally matching spatially and temporally variable vegetation cover (although data were filtered for vegetation by Nissen et al. 2014).

By using TLS to capture the displacement field in cm-scale resolution, we show that the spatial extent of the zones of horizontal and vertical diffuse off-fault deformation varies from ~8 m in the horizontal to ~4 m in the vertical. In addition, ~50% of the horizontal deformation is accommodated in a distributed manner away from the discrete surface rupture whereas only ~16% of vertical deformation occurs away from the discrete fault. This suggests that more of the horizontal extension associated with normal faulting does not reach the surface (compared to the vertical deformation), indicating that the shallow slip deficit here is partitioned. This occurs due to partitioned off-fault deformation and can be explained by several potential mechanisms. A simple elastic dislocation model can explain the first order partitioned deformation field if the fault dip steepens in the shallow sub-surface and a shallow synthetic fault and/or antithetic faulting accommodates some deformation in the immediate near-field of the primary fault (i.e. <30 m depth and <20 m distance from the primary fault; Figures 4e and S21). Steepening the dip of the fault close to the surface has the effect of disproportionately inducing a near-surface shallow horizontal displacement deficit, while the effect on the vertical displacement field is smaller. Distributed deformation dominated by opening on a network of shallow fractures could

also contribute to the partitioned off-fault deformation. Despite these models being non-unique and simplistic, they give some indication of potential first order processes affecting near-fault deformation. Intriguingly, partitioned distributed deformation was also observed by Scott et al. (2018) in the 2016 Kumamoto strike slip earthquake, but in the opposite sense, with vertical deformation twice as distributed as horizontal deformation. This observation suggests that the orientation of the principal compressive stresses (i.e.  $\sigma_1$  is vertical for normal faults and horizontal for strike-slip faults) may also play a role in facilitating distributed off-fault deformation.

The implications of our results and illustrative modelling are that partitioned off-fault deformation could be caused by a combination of changes in near-surface fault geometry and off-fault deformation taken up on a diffuse network of faults. Consequently, the total slip in a prehistoric earthquake or cumulative fault scarp may be underestimated if only a narrow fault zone is investigated or if off-fault deformation is poorly preserved in the landscape. Overall this highlights the need for more high-resolution near-fault studies of co-seismic deformation.

## **5 Conclusions**

We collected terrestrial laser scanning data from a section of the Mt Vettore-Mt Bove fault system shortly before and after the  $M_w$  6.6 Norcia earthquake in 2016. Using ICP differencing to calculate co-seismic deformation, we find evidence for discrete vertical deformation, with a small component ( $\sim 16\%$ ) of distributed deformation limited to a narrow 4 m-wide zone. In contrast, horizontal extension shows a smaller discrete surface offset and  $\sim 50\%$  of the extension is accommodated as off-fault distributed deformation over an 8 m-wide zone. These first differential TLS observations of co-seismic slip at this scale reveal insights into the partitioning

of the co-seismic off-fault deformation and the nature of distributed shallow slip that are not resolvable using airborne lidar, satellite radar interferometry, or most traditional field surveying techniques.

### **Acknowledgments and Data Availability**

This work was supported by NERC Urgency grant NE/P018858/1. The TLS data are available on OpenTopography (<http://www.opentopography.org>). The pre-earthquake data is available at: <https://doi.org/10.5069/G9JQ0Z4H>. The post-earthquake data is available at: <https://doi.org/10.5069/G9CV4FV2>. We thank Paolo Marco de Martini for his generous assistance with our fieldwork, Eutizio Vittori for alerting us to the surface ruptures of the Visso Earthquake and Ed Nissen for help with the ICP code. Figures were made using the Generic Mapping Tools (Wessel and Smith, 1998). We thank Mike Oskin, an anonymous reviewer and the associate editor for their helpful reviews that improved this paper.

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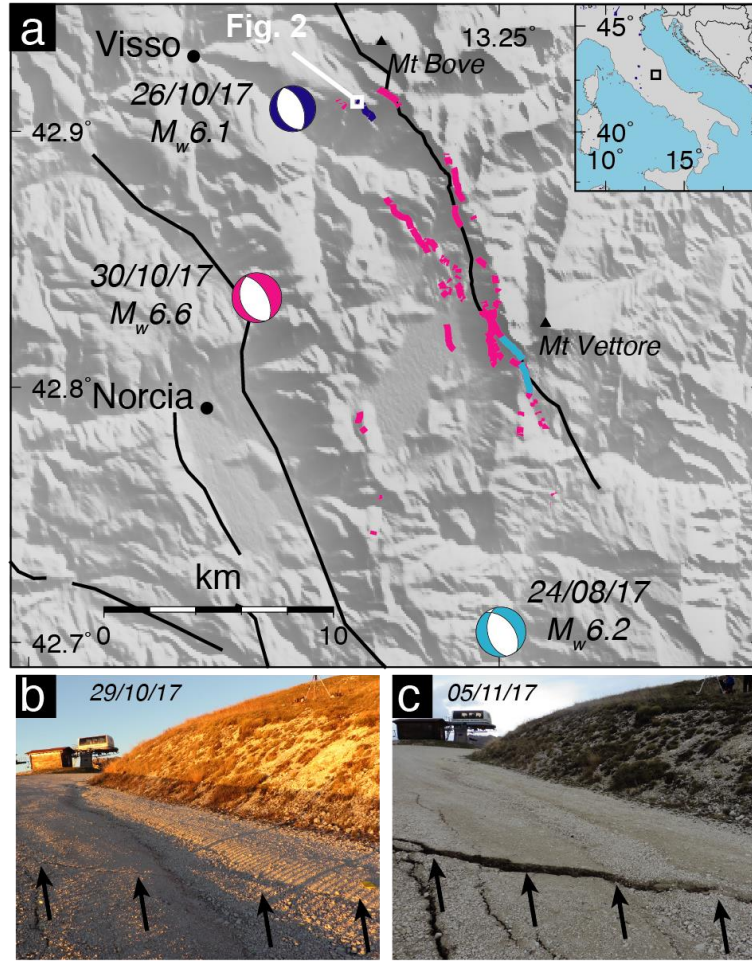
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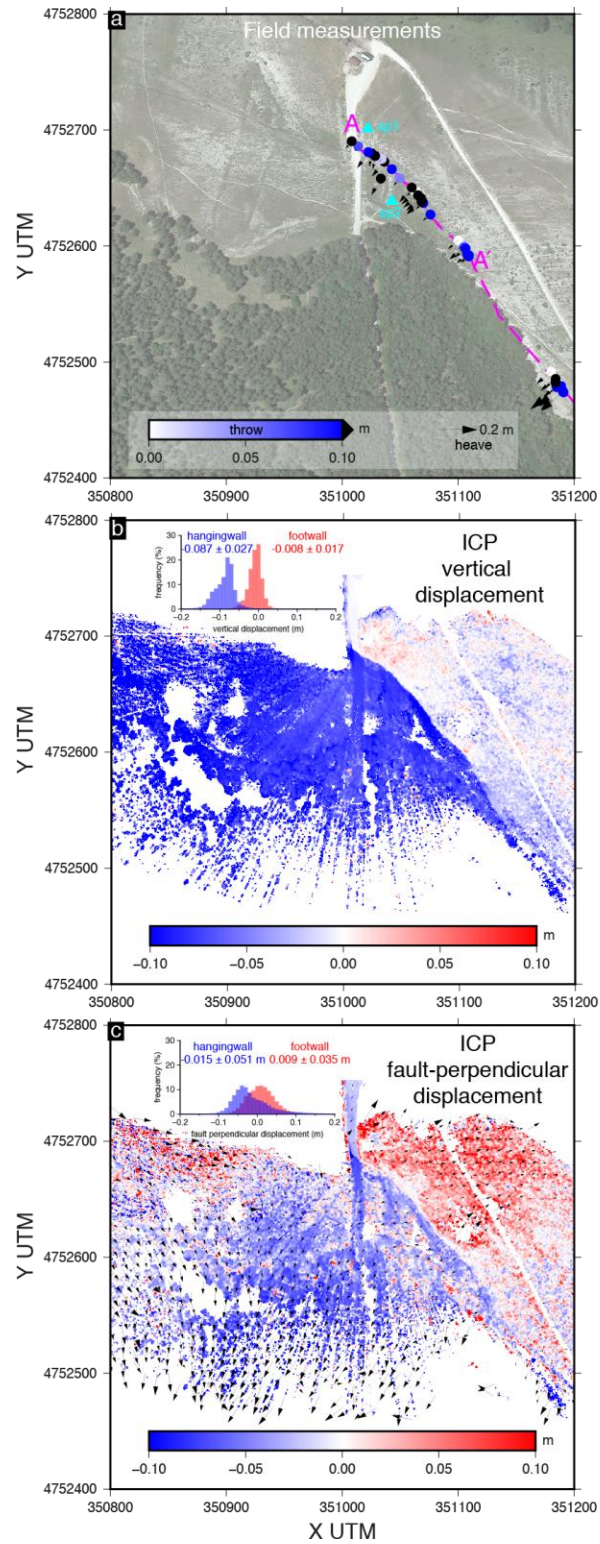
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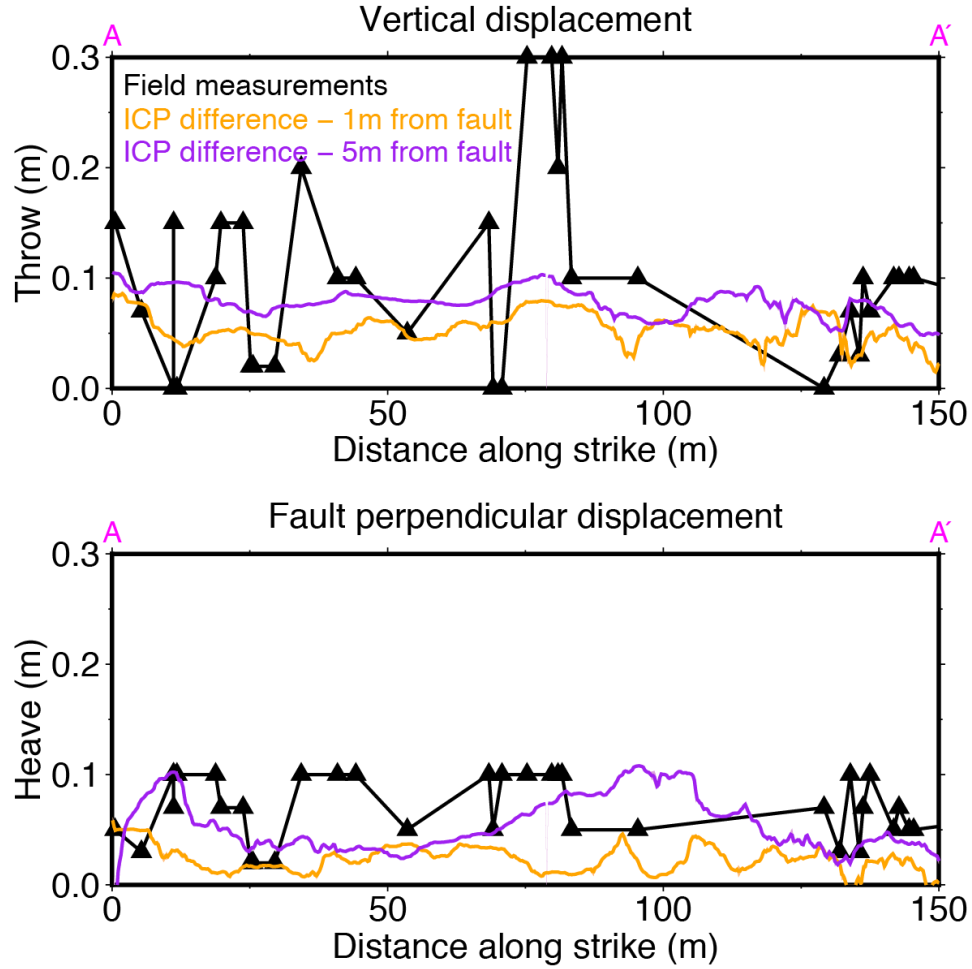
**Figure 1. a)** Map of the central Apennines, Italy, showing the location of the events in the 2016 central Italy earthquake sequence and the study area (focal mechanisms are composite geodetic solutions from Walters et al., 2018 with locations from Chiaraluce et al., 2017). Surface ruptures for the  $M_w 6.2$  (light blue) and  $M_w 6.1$  (dark blue) earthquakes were both re-ruptured and overprinted by the  $M_w 6.6$  earthquake (magenta). The offset between the focal mechanism and the surface ruptures of the  $M_w 6.2$  earthquake is due to the complex rupture of the earthquake which spanned two faults: the Mt Vettore fault, (shown here) and the Laga fault to the south. **b)** The study site 12 hours before the  $M_w 6.6$  Norcia earthquake showing the small c.1 cm offset

caused by the  $M_w$  6.1 Visso earthquake. **c)** The study site following the  $M_w$  6.6 Norcia earthquake.

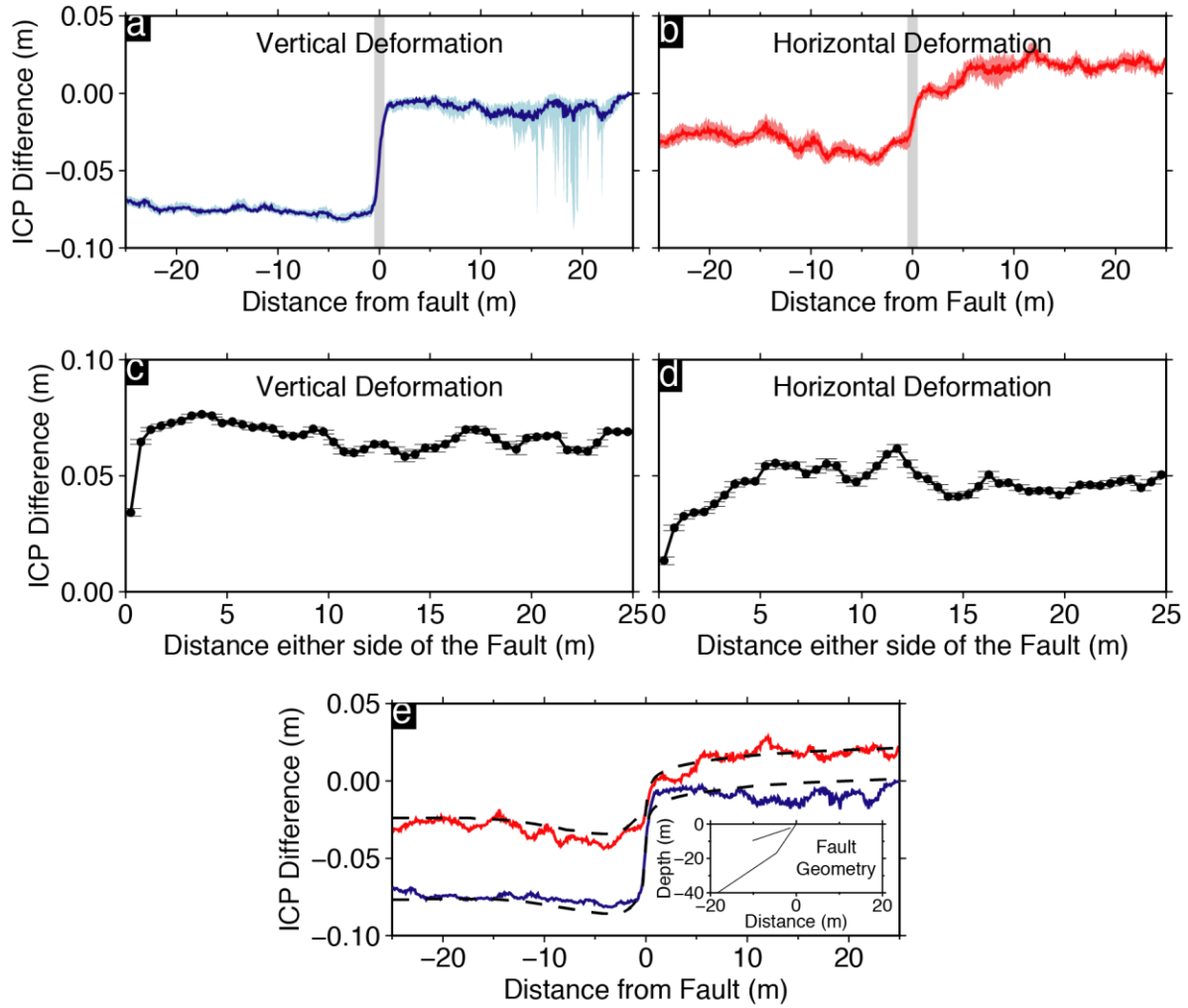


**Figure 2.** a) Google earth image of the fault section near to Frontignano where we collected a pre- and post-earthquake terrestrial laser scan. The location and magnitude of the surface rupture

is also indicated. **b)** ICP vertical displacements from the M 6.6 Norcia earthquake. The inset histogram is plotted with a bin-width of 0.01 m, with the hangingwall (blue) and footwall (red) points selected either side of the distinct offset observed in the ICP vertical displacement field. **c)** ICP horizontal displacements. The arrows show the vectors of the horizontal displacement (see part a for scale). The underlying colours are the horizontal displacements resolved perpendicular to the mean fault strike across the segment. The inset histogram uses the same points as part b to compare the footwall and hangingwall displacements. The ICP displacement field in parts b and c have been gridded at 1 m resolution in this figure.



**Figure 3.** Along strike ICP results and field measurements. The field measurements were collected using measuring tapes, rulers and compass clinometers with matching points identified on either side of the fault to precisely measure throw, heave and slip direction (Villani et al., 2018). The field measurements are plotted alongside the median difference between the footwall and hangingwall ICP results at 1 m and 5 m from the fault calculated in 25 cm sections along strike.



**Figure 4.** **a)** Across strike bootstrapped medians of the ICP vertical displacement between A and A' in Figure 2a. The light blue area shows the range of medians of the individual bootstrap samples. The thick blue line is the mean of these samples. **b)** Across strike bootstrapped medians of the ICP horizontal displacement between A and A' in Figure 2a. The light red area shows the range of medians of the individual bootstrap samples. The thick red line is the mean of these samples. **c)** The difference between the bootstrapped samples of vertical displacement from the hangingwall and footwall at distances in 0.5 m intervals from the fault. **d)** The difference between the bootstrapped samples of horizontal displacement from the hangingwall and footwall at distances in 0.5 m intervals from the fault. **e)** Predicted displacements (dashed lines) of

horizontal (red) and vertical (blue) ICP displacements from our elastic model (Okada, 1985; Coleman and Li, 1996). The fault geometry is shown in the inset. See supplementary materials for more information on the modelling.

